"On the Relation of Artificial Colour-blindness to Successive Contrast."

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I have elsewhere pointed out that my observations on artificial colour-blindness seem unfavourable to the theory of Hering, and favourable to that of Young. The experiments on successive contrast described in the following pages tend also to confirm in a remarkable manner opinions held before the time of Young, and which must be considered as incorporated in his theory. The method I have pursued throughout this investigation consists essentially in the use of the spectroscope to analyse sensations of contrast, and I have accordingly been able to make certain experiments which would have been beyond the resources of those earlier writers; but the following account of their opinions, expressed as far as possible in the words of the authors themselves, is intended to show in some detail how closely their views agree with my own results.

During the 18th century the phenomena of after-images and successive contrast attracted a good deal of attention, and although in most cases the physical conditions of the experiments were too complex to afford much information as to their true nature, there were some remarkable exceptions, to which I desire to direct attention.

The opinions enunciated during the 18th century may be divided broadly into two groups. The one school held that after the stimulus of a strong light of any given colour, a species of reaction sets in, by which a sensation of the complementary colour is produced. This view may be regarded as belonging to the same category as the theory of Hering. It may be doubted whether it was definitely adopted by Jurin,* who says only that this "contrary sensation is apt to arise in us sometimes of itself, and sometimes from such causes as at another time would not produce the sensation at all, or at least not to the same degree," and preserves a like caution throughout his description of the phenomena. Other experimenters, however, advocated this theory, and it was strongly upheld in 1801 by Venturi,† who maintained that the changing tints of after-images excited by the pure colours of the spectrum proved the existence of a multiple function for each nerve-fibre, as opposed to the theory of one nerve, one function, taught by Bonnet.‡

* "Essay on Distinct and Indistinct Vision." In Smith's 'Opticks,' 1738.

† "Dei Colori Immaginarii." 'Opusc. scelti sulle Scienze,' da Carlo Amoretti. Soave, vol 21, p. 274.

‡ "Essai Analytique sur l'Âme," and "Essai de Psychologie." Works. 1785.

The other school, from which the theory of Young may be considered to have developed, seems to have been founded by Scherffer, who, in 1761, published a long series of experiments on contrast based on Buffon's work, but criticising his conclusions. Scherffer's standpoint is briefly expressed in the following passage:—

"Perhaps the Creator has so constructed the entire organ of vision that each kind of ray can only act upon such of the parts of which the eye is composed as are particularly appropriated to it. But I presuppose that the whole action of light consists in attraction and repulsion. . . . . It may be that a continuous action of, for instance, red light, may so change the order and arrangement of the parts of the back of the eye . . . . that those rays may be no longer strong enough to communicate to these parts the necessary vibratory movement, until a little rest shall have restored them to their condition . . . . and during this time the other rays of different kinds will not cease to act . . . ."

He points out that if this explanation of "accidental colours" is the true one, it must follow that the after-image of a coloured object viewed upon a ground of the same colour must be black, just as a white spot upon a dark ground gives a black after-image upon white paper.*

Two of his experiments may be specially noted:—

In order to determine the complementaries of the primary colours by experiment, he projected the solar spectrum on a white surface, and observed the colours of the after-image produced by it.† He then compared these with the corresponding colours, as calculated by Newton's method. He gives the following list of colours observed:—

Red	Blue, verging on green.
Orange	Blue, almost indigo.
Yellow.......................	A more violet-blue.
Green	Purple.
Blue..........................	Red.
Indigo	Orange, but rather pale.
Violet	A very yellow green.

He also made drawings of flowers, and painted them with colours complementary to those they naturally possessed. These, when steadily looked at in a bright light, gave after-images in their true colours. He even went so far as to copy a picture, painting it with a green face shaded with yellow, white hair and eyebrows, black eye-balls with white pupils, and green lips, so that the accidental image of it had the colours of the original.‡

* Compare this paper, Section II (2), p. 208.

† Compare this paper, Section II (1), p. 208.

‡ Compare this paper, Section III, p. 213.

He does not, however, deal with the positive after-image and after-effects. This was done by Robert Waring Darwin,* in his paper on the "Ocular Spectra of Light and Colours," in which he treats of the "direct and reverse spectra" of brightly illuminated pieces of silk of various colours. He describes very clearly the series of changes of these after-images from negative to positive and back again, observable under certain conditions, and points out that in order to see the direct spectrum (positive after-image) all extraneous light must be excluded, whereas "it is difficult to gain the reverse spectrum (negative after-image) where there is no lateral light to contribute to its formation." "The reverse spectrum is instantaneously converted into the direct spectrum by excluding lateral light, and the direct into the reverse by admitting it. . . . ." "The green spectrum which is perceived on removing the eye from a piece of red silk to a sheet of white paper, may either be called the reverse spectrum of the red silk, or the direct spectrum of all the rays from the white paper except the red, for in truth it is both." Thus the "direct spectrum" is the sensation of each colour persisting after the cause that produced it has ceased to act, and the "reverse spectrum" is the effect of compound colours upon the retina, which still remains liable to be excited "by any other colours except the colour with which it has been fatigued." He proves this by showing that the colour of the "reverse spectrum" depends upon that of the "lateral light," *i.e.*, the light which reaches the eye after the retina has been fatigued.† He compares these phenomena with those of taste, touch, and hearing, and shows that each of these senses undergoes a partial temporary paralysis after being strongly excited. Although, therefore, the unaided evidence of the senses might have suggested that each pair of complementary colour-sensations, such as red and green, or blue and yellow, were conjugate functions of some nerve structure, it is plain that he desired to emphasise the fact that they must be regarded as due to separate nerve structures. One nerve, one sensation. The sensation might be weak or strong, according to the physiological condition of the organ at the time, but its character could not be changed.

Darwin, following Newton, refers to seven colours as primaries. In 1792 Wünsch,‡ whose method consisted in the superposition of spectra projected upon a screen, stated that a mixture of three colours, namely, red, green, and violet-blue, could be made to match any given tint.

For the basis of Young's theory there existed, therefore, experimental evidence of the small number of the primary colour-sensations, and of their being functions each of some nerve structure specially

* 'Phil. Trans.,' vol. 76 (1786), p. 313.

† Compare this paper, Section II (1), p. 208, and Section III, pp. 212, 216.

‡ 'Ueber die Farben des Lichtes.' Leipzig, 1792.

appropriated to it. The phenomena of negative and positive after-images were known—it was known that certain colours are altered in hue to an eye previously exposed to coloured light, and that experiments on this subject should be made with the spectrum rather than with pigments.

The following papers also are of special interest in connection with the present communication.

Brewster,* by looking at the spectrum through a coloured medium, was able to trace the green as far as C. His mode of explaining the phenomenon led to a controversy, in which the true merit of the observation was lost sight of. A momentary colour-blindness is, in reality, as was shown by Hunt, produced by the contrast of adjacent parts of the spectrum differing greatly in brightness.

Piazzi Smyth,† working with a very long spectrum, observed the boundaries of the colours to change when any alteration was made in the intensity of the illumination.

The earliest account of a systematic investigation of the effect of retinal fatigue on the colours of the spectrum is in a paper of John Aitken.‡ Similar observations were made by Edmund Hunt,§ who also describes the appearance of the spectrum when observed through certain coloured media, after the manner of Brewster. Coloured figures of the results are given. Both these authors used light much less intense than that employed by me, and did not obtain the full effect. I was not aware of their work until after my own paper had been read, and therefore take this opportunity of calling attention to it. To these may be added a paper by Hess‖ on the Alterations of the spectral colours by retinal fatigue.

II.—*Experimental Investigation of the Phenomena of Successive Contrast.*

Successive contrast is an effect of two stimuli—a primary stimulus by which the retina is fatigued, and a secondary stimulus, the effect of which is modified in consequence of the first. The colour-sensations excited may be reduced to four at the most. To arrive at the fundamental laws of contrast, we may vary the conditions in the following manner :—

Let the first stimulus excite a single colour-sensation, taking each in turn, or separated from the rest as in the spectrum. Four cases arise :

(1.) The second stimulus may excite all the sensations, *i.e.*, it may consist of white light.

* 'Edin. Trans.,' vol. 12 (1834), p. 132.

† 'Roy. Soc. Edin. Trans.,' vol 28 (1879), p. 792.

‡ "Colour and Colour-Sensation," 'Roy. Scot. Soc. of Arts Proc.,' 1871–72.

§ Hunt, 'Colour Vision,' Glasgow, 1892.

‖ Graefe's 'Archiv für Ophthalmologie,' 36, abth. 1, pp. 1—32.

This gives the complementary colour, *i.e.*, the direct spectrum, as Darwin calls it, of all the colours save that excited by the first stimulus.

(2.) The second stimulus may excite the same sensation as the first, but less strongly.

This gives a black after-image.

(3.) The second stimulus may excite two or more colour-sensations, including that of the first stimulus.

The colour of the resulting image is that of the second stimulus *minus* the first.

(4.) The second stimulus may excite one or more sensations, none of which were included in the first stimulus.

The colour of the resulting image is that of the second stimulus *plus* an admixture, usually small, of the first.

This scheme is covered by the experiments described in the following pages. They are so arranged as to require but little special apparatus, and to employ spectral colours by direct observation. Some little care must be taken to adjust the relative intensity of the two stimuli correctly, and to effect the change from one to the other as suddenly as possible.

1. *After fatiguing the retina by the spectrum, to observe a uniform white light.*

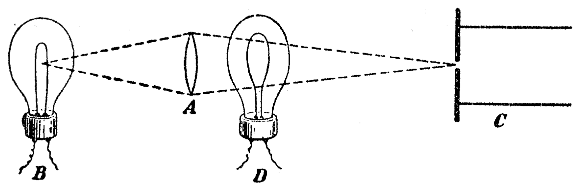
This is most easily done by means of a low-power spectroscope with a reflected-scale tube. Unscrew the cap containing the scale, and place a mirror so as to reflect white light from the sky into the tube. Cover the open end of the scale tube by a black card held in the right hand, and have a similar card in the left hand in readiness to cover the slit of the spectroscope. Let the slit be fairly wide so as to give a rather bright spectrum. Look steadily at the spectrum for half a minute, keeping the eye fixed on the intersection of the cross wires, and then suddenly cover the slit and uncover the scale tube. A complementary spectrum will be seen, brilliantly defined, for a fraction of a second. To myself, by daylight the spectral red is replaced not by green, but by blue, and the complementary of green is a pinkish purple, but by lamp-light the complementary of red is green, and that of green is red. The advantage of this mode of experimenting is that it utilises existing apparatus.

2. *After fatiguing the retina by the spectrum to observe a less intense spectrum.*

The phenomenon of successive contrast is shown by the preceding method in its least simple form. To analyse it, the effect of retinal fatigue by each spectral colour on the perception of that same colour must be determined. This may be done by focussing with a lens A (fig. 1) a glow lamp B on the slit C of an ordinary spectroscope, and at the same time illuminating it by a second glow lamp D placed between

the lens and the slit. The effect produced is that of a broad, continuous spectrum, with a narrow but much brighter spectrum in the middle of it. After a few seconds a black card is suddenly brought behind the lens, so as to screen off the light of the focussed lamp B. A dark band like a shadow instantly appears in place of the narrow bright spectrum—that is to say, *the effect upon the retina of light of any wave-length is to blind the eye temporarily for light of that same wave-length.* This may be illustrated in another way. Place near the slit of the spectroscope a

FIG. 1.



Bunsen burner, and behind it, a few inches farther off, a lamp, and hold between the lamp and the Bunsen flame a black card. Burn some calcium or strontium chloride, or common salt, or anything that gives a good bright-line spectrum, in the Bunsen flame, keeping the eye fixed on one of the lines. On snatching away the card and the Bunsen flame a dark-line spectrum will be seen momentarily against the continuous spectrum of the lamp, so sharply defined that it is difficult to realise that it is merely an illusion.

These results are of cardinal importance. They mean that the green or blue subjective impression produced by a white surface when the eye has been fatigued for red does not indicate that red excites an after-sensation of green or blue, or renders the eye more sensitive to green or blue, but that the eye has become less sensitive to red. And similarly with the other colours. This point is clearly brought out by Darwin. An "accidental" colour has therefore this in common with an absorption spectrum—that it involves a diminution of the intensity of a certain portion or portions of the spectrum.

The line of proof is completed by the third disposition of the variables.

3. *After fatiguing the retina by any one colour, to observe the entire spectrum.*

This is in effect a mere variant of the method described in my paper,* and depends on the production of a very transient colour-blindness. It is necessary to make special arrangements for suddenly substituting a complete spectrum for a field of view illuminated by monochromatic light. Among the methods I have tried, the following may be mentioned :—

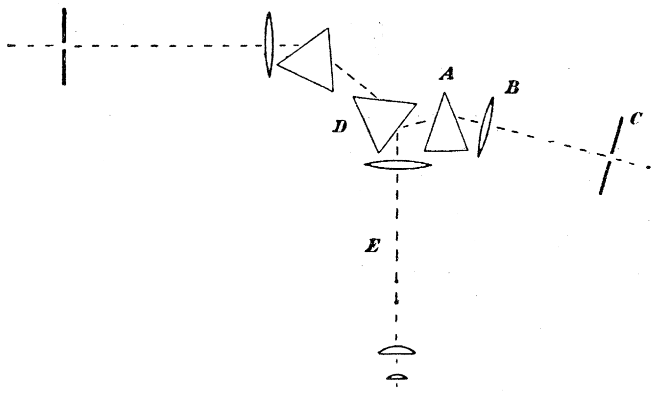
* 'Phil. Trans.,' B, vol. 191 (1899), p. 4.

(1.) Place a coloured screen over the end of the scale tube of an ordinary spectroscope, the scale being removed, and cover the slit with a card. After looking at the coloured light for some seconds, cover the scale tube, and simultaneously uncover the slit. This experiment is easily tried, but is open to the objection that the first stimulus is not perfectly monochromatic.

(2.) Illuminate the scale tube with monochromatic light from a prism, and proceed as before This plan obviates the difficulty referred to, but does not afford sufficient light to produce the ful effect.

(3.) A single prism A, fig. 2, with collimator B, and slit C, is fixed

FIG. 2.



near the back surface of the last prism D of the large spectroscope in such a position that the rays from it are reflected into the telescope E of the large spectroscope. This second spectrum is of course much fainter than the one observed directly through the instrument, but that is an advantage rather than otherwise. It is only necessary to arrange two black cards with slits in them in such a way that when light passes through the first spectroscope the second is obscured, and on touching a spring the conditions are reversed.

In order to make the effects more marked, a short slit should be used for the large spectroscope, so that it may give a band of monochromatic light across the middle of the field, fairly bright but rather narrow. The eye should be fixed on the centre of this band. After a few moments, by the action of the spring referred to, a black card is suddenly brought over the slit of the spectroscope, shutting off the light, while at the same moment the screen is removed from the other spectroscope, and the complete spectrum appears, filling the entire field of view. For an instant, a dark shadow is seen, not extending

across the entire spectrum, but only that part of it corresponding to the colour-sensation excited by the monochromatic light. The effect is very striking after red light. An intensely black band cuts through the spectrum from the ultra-red, as far as C, where it begins to fade away into a pure green.

After violet light, a similar black band cuts through the spectrum from the ultra-violet, and if care has been taken not to implicate the blue in the fatigue, the black band fades away into blue.

After green light, most frequently the red and blue are seen to stretch across and meet in the middle of the *b* lines; but sometimes, if the exposure is exactly right, a well-marked darkening of that part of the spectrum is seen.

Blue light is the most difficult to manage, unless a wide dispersion is used, the blue being otherwise not sufficiently separated from the green and the violet. After getting the adjustments right, it is better either to wait ten minutes, or use the other eye. With these precautions, it is easy to see the green and violet meet in the place of the blue, and to note that the after-image of the blue casts no shadow on the violet near H. Sometimes a momentary shadow may be seen in the blue. This experiment is of interest as affording additional evidence of the existence of a separate sensation for blue.

It should be noted that the two spectra must have the corresponding colours on the same side. If the prism of the second spectroscope is reversed so as to bring the red of one spectrum towards the violet of the other, a black shade, very well defined, can be produced in *any part of the second spectrum.* For if the two spectra are so arranged that any given portion of the one corresponds with the same wave-length on the other, then no part of the one spectrum on either side of that one part will be of equal wave-length with the portion of the other spectrum which coincides with it. Accordingly, a negative after-image will be produced only of the short space within which the wave-lengths are approximately the same. But it is clear that such an experiment is more curious than useful.

III. *Contrast Phenomena by Intermittent Stimulation.*

In 1868 Sigmund Exner* made a series of experiments on the following plan. After an interval of darkness, he presented to the eye, for a fraction of a second, the image of a small white disc. This was succeeded by a disc of considerably larger diameter, which in turn was followed by darkness. The illumination of either disc, and the period during which it was visible, could be independently varied. Thus the portion of the retina on which fell the image of the small disc received

* Exner, 'Sitzungsberichte d. Wiener Akad.' Abth. 2, vol. 58 (1868), pp. 601—632.

not merely the light of the larger disc, but in addition the light of the smaller disc. Yet in spite of this, with certain relations of intensity and duration between the two images, the total sensation evoked by the larger quantity of light was less, so that the small disc appeared as a black spot on the larger disc. I was curious to ascertain to what extent this principle could be carried. By the following experiment it may be demonstrated in a striking manner. A cardboard disc, A, figs. 3, 4, 200 mm. diameter, of which 180° is black and

FIG. 3.

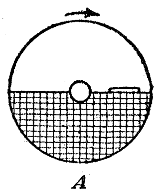
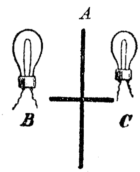


FIG. 4.



the rest white, has a slit about half a millimetre wide cut at the junction of black with white. It is made to revolve so that black precedes and white follows the slit. An incandescent lamp B is placed behind the disc, and another C in front of it, so as to throw a strong light upon its surface. While the disc is moving slowly the incandescent filament of the lamp B, seen through the slit as it passes across, looks bright against the white card, but when a certain speed is reached it appears as a black thread against a brighter background.

In spite of the very short duration of the intense light of the filament, the fatigue induced by it is out of all proportion to the sensation it excites, and in consequence the less fatiguing illumination of the white card produces a greater effect on the senses than the sum of the sensations due to the filament and the subsequent light. With a single flash the filament looks, to the rested eye, black all over, but with a succession of flashes there is generally an appearance as though the luminous filament were partly covered by an opaque black thread, but could be seen in places behind it. This I think is due to the shifting of the images on the retina, which after the first flash is no longer in a uniform condition. The retina is, as it were, scarred with after-images, and the ratio of illumination to length of flash which suits one part is incorrect for another.

When a red glass is placed over the lamp the reversed image of the filament is green if the card is not quite white, or if the light falling on it is yellowish, but blue-green or blue if it is illuminated by sunlight or the arc lamp. The use of coloured glasses, however, so far diminishes the light that in most cases a disc with a different flash ratio has to be employed, and the lamp C placed at a greater distance.

I next attempted to get the reversed image of the sun. This was attended with difficulty, owing to the lack of a disc with a slit sufficiently fine to reduce the sensation evoked by the direct light of the sun within the limits required. I succeeded at last by increasing the intensity of the illumination of the white card. This was effected by holding in front of it a large lens by which the sun's rays could be concentrated, the degree of concentration being regulated by adjusting the distance of the lens from the card. In this way I was able to see the sun's disc black upon a white ground. The experiment tended to confirm the explanation already given of the appearance of the incandescent filament under similar conditions. If the visual axis was not fixed, three or four black discs would appear, and on looking directly at one of the more central ones, the sun's disc seemed to be partly visible behind it. A very curious effect was produced by "sweeping" with the eye along a faint circle marked on the revolving card. A whole series of black discs started into view one after the other without a glimpse of the luminous disc that produced them.

The principle underlying Sigmund Exner's method is illustrated in an even more striking manner by the remarkable experiment of Shelford Bidwell. In this a coloured object is placed behind a disc half black and half white, with a sector 30° wide cut out of the white portion. As the disc revolves, the eye is kept in darkness for a space, then sees the coloured object for a short time, and immediately afterwards a white surface for a considerably longer time. The retinal fatigue induced by the colours of the object causes a negative after-effect so strong that the object is seen in its complementary colours.

From the point of view of my own investigations it was necessary to repeat these experiments with the pure colours of the spectrum. There are several positions in which a disc, such as Shelford Bidwell employs, can be used in conjunction with a spectroscope. It may be placed between the prism and the telescope, the latter being set back an inch or two to make room for it, or it may work in a gap cut in the body of the telescope, being illuminated by front light through a side tube. But either arrangement involves some alteration of the spectroscope. The following method is free from this objection and has a certain interest of its own:—

The disc is placed in front of the eye-piece of the spectroscope, and the spectrum viewed through a second telescope fixed in the optic axis an inch or two from the eye-piece. But the second telescope magnifies the spectrum and consequently renders it less bright. The definition is, however, much better than would be expected, and is so little affected by slight displacement of the second telescope from the optic axis that it occurred to me to try the arrangement shown in figs. 5, 6.

A telescope A, magnifying ten times, is placed with its eye-piece close to the eye-piece E of the spectroscope. The disc B revolves

between the objective of A and the objective of a second telescope C, magnifying five times. The first telescope A being inverted, diminishes the image to one-tenth of its size, and the second telescope only magnifies it five times, so that it appears to the eye half the size it would without the telescopes, and correspondingly brighter. Although the two telescopes were merely supported by

Fig. 5.

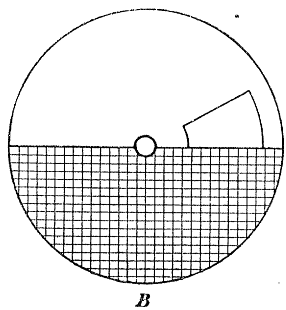
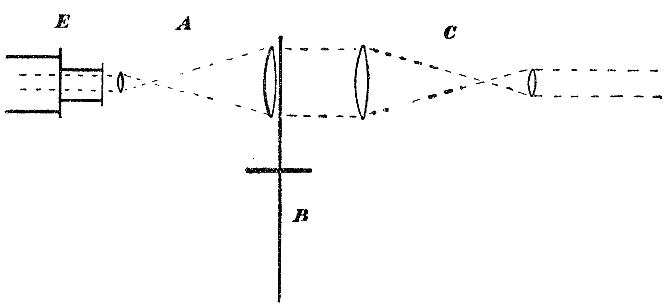


Fig. 6.



retort stands and roughly adjusted, the definition was quite good enough and the light strong enough to show the complementary spectrum extremely well.

But the white light used was merely that reflected from card, and was in consequence weak in the extreme violet rays. By the following arrangement white light reflected from a mirror may be employed:—The disc A, figs. 7, 8, which is 25 cms. in diameter, has two sectors of 30° aperture, and reaching within 2 cms. of the centre, cut away at opposite ends of a diameter. The disc B, 15 cms. in diameter, has two narrow slits of about 1° or 2° aperture and 180° apart. Both discs are blacked and mounted upon the same shaft, which is furnished with a nut and broad washer, so that they can be clamped together. The

shaft is so fixed that the slits of the smaller disc may revolve close in front of the slit C of the spectroscope, an ordinary single-prism instrument, furnished with a reflected-scale tube, the scale being removed, leaving the tube open. A mirror placed at D in front of the sectors of the larger disc reflects light from the sky on to a second mirror E, by which it is reflected into the scale tube, causing the field of view to be filled with a soft white light.

FIG. 7.

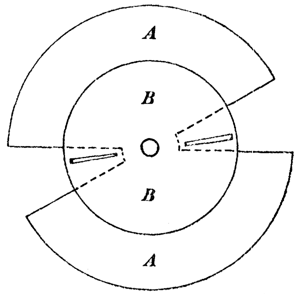
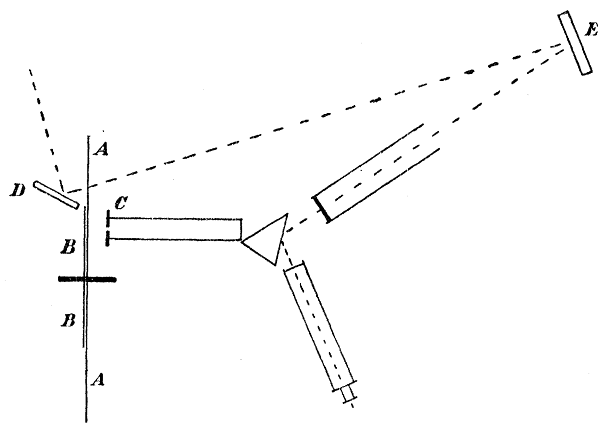


FIG. 8.



The mirrors and discs must be adjusted until on rotating the shaft slowly the flashes occur in the following order:—First a sharp flash through the small disc, giving a momentary view of the spectrum. As soon as possible after this is over, but not before, there is a rather long soft flash of pure white light, followed by a much longer period of perfect darkness. The reason for having two slits and two sectors on the discs is simply that they may be well balanced on the shaft, and therefore rotate more steadily. There should be no overlapping

of the spectral flash by the white flash, a short interval of darkness between them being preferable to the smallest overlap. For this reason the shaft is fitted with a screw nut, which being slackened, the angular position of the slits with respect to the sectors can be accurately adjusted. On rotating the discs steadily, but not too quickly, a spectrum of complementary colours is seen with the greatest distinctness. By placing a narrow strip of black card across the mouth of the scale tube, a portion of the white flash may be stopped out, allowing the normal spectrum to be seen in that part of the field. It is necessary, however, to shade the corresponding part of the slit somewhat, so that the normal spectrum may not overpower the complementary spectrum. The colours as I see them are as follows:—Red is replaced by Prussian blue, green by purple (a red shade of Hoffmann's violet), blue by orange, and violet by yellow. To show the complementary of violet it is necessary to use sunlight, or, better still, the arc light. I have never been able to see it properly by any of the methods involving the use of white card or paper surfaces as reflectors.

The experiments of Section 3, for which a wide dispersion was required, were made with a large direct-vision spectroscope belonging to the Marlborough Collection, for the use of which I am indebted to the Aldrichian Demonstrator of Chemistry, Mr. W. W. Fisher. I have also to thank Professor Gotch for the use of the electric light in the physiological laboratory. The remainder of the work was done at Reading College, and the expenses have been defrayed by a portion of the sum of £10 allotted to me by the Royal Society out of the Government Grant.

"On the Production of Artificial Colour-blindness by Moonlight."

By George J. Burch, M.A. Oxon., Reading College, Reading. Communicated by Professor Gotch, F.R.S. Received January 30,—Read February 8, 1900.

Since the publication of my paper on "Artificial Colour-blindness"* I have found a very general and not unnatural tendency to regard the results described therein as phenomena of a pathological condition induced by the severe strain to which the structures of the eye had been subjected. In my paper I indicated, perhaps too briefly, that this could not be the case, since "the same general phenomena are observable alike with strong sunlight and with the faintest light the eye is capable of perceiving."

The purpose therefore of the present communication is to describe some of the experiments on which that statement was based.

* 'Phil. Trans.,' B, vol. 191 (1899), p. 1.